

Extraction of a_1 and a_2 from $B \rightarrow \psi K(K^*)$, $D(D^*)\pi(\rho)$ Decays

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Abstract

Based on the factorization approach, we show that the CLEO data for the ratio $\Gamma(B \rightarrow \psi K^*)/\Gamma(B \rightarrow \psi K)$ and the CDF measurement of the fraction of longitudinal polarization in $B \rightarrow \psi K^*$ can be accounted for by the heavy-flavor-symmetry approach for heavy-light form factors provided that the form factor F_0 behaves as a constant, while the q^2 dependence is of the monopole form for F_1 , A_0 , A_1 , and of the dipole behavior for A_2 and V . This q^2 extrapolation for form factors is further supported by $B \rightarrow K^*\gamma$ data and by a recent QCD-sum-rule analysis. We then apply this method to $B \rightarrow D(D^*)\pi(\rho)$ decays to extract the parameters a_1 and a_2 . It is found that $a_1(B \rightarrow D^{(*)}\pi(\rho)) = 1.01 \pm 0.06$ and $a_2(B \rightarrow D^{(*)}\pi(\rho)) = 0.23 \pm 0.06$. Our result $a_2/a_1 = 0.22 \pm 0.06$ thus significantly improves the previous analysis that leads to $a_2/a_1 = 0.23 \pm 0.11$. We argue that, contrary to what anticipated from the leading $1/N_c$ expansion, the sign of $a_2(B \rightarrow \psi K^{(*)})$ should be positive and $a_2(B \rightarrow \psi K^{(*)}) \gtrsim a_2(B \rightarrow D^{(*)}\pi(\rho))$.

1. Introduction The fact that the D^+ meson has a longer lifetime than the D^0 is already manifest at the exclusive two-body decay level: The number of two-body D^+ decay modes is about two times less than that of the D^0 and there exists a large destructive interference in the Cabibbo-allowed decays $D^+ \rightarrow \bar{K}^0\pi^+$, $\bar{K}^0\rho^+$, $\bar{K}^{*0}\pi^+$, which is also known as the Pauli interference at the inclusive level. The recent CLEO data on $B \rightarrow D\pi$, $D\rho$, $D^*\pi$, $D^*\rho$ decays exhibit a rather unexpected result [1]: The interference between the two different amplitudes contributing to exclusive two-body B^- decays are evidently constructive, contrary to the charmed meson case. This feature is quite stunning since the rule of retaining only the leading terms in the $1/N_c$ expansion (N_c being the number of color degrees of freedom) [2], which is empirically operative in charm decays, fails in $B \rightarrow D^{(*)}\pi(\rho)$ decays. Quantitatively, the ratio of the parameters a_1 and a_2 corresponding to the external and internal W -emission amplitudes is found to be positive with the magnitude $a_2/a_1 = 0.23 \pm 0.04 \pm 0.04 \pm 0.10$ [1].

Under the factorization assumption, the spectator meson decay amplitude is characterized by the parameters a_1 and a_2 [3] which are related to the Wilson coefficients c_1 and c_2 by

$$a_1 = c_1 + \xi_1 c_2, \quad a_2 = c_2 + \xi_2 c_1. \quad (1)$$

Naive factorization implies that a_1 and a_2 are universal, namely they are channel independent in D or B decays. Recently, we have shown from the analysis of experimental data that a_2 is not universal at least in charm decays [4]. We found $a_2 \sim -0.51$, $-(0.66 \sim 0.78)$, $-(0.85 \sim 0.91)$ respectively for $D \rightarrow \bar{K}\pi$, $\bar{K}^*\pi$ and $\bar{K}^*\rho$ decays [4]. Physically, this can be understood as follows. Writing

$$\xi_1 = \frac{1}{N_c} + \frac{r_1}{2}, \quad \xi_2 = \frac{1}{N_c} + \frac{r_2}{2}, \quad (2)$$

where $r_{1,2}$ denote the contributions of color octet currents arising from the Fierz transformation relative to the factorizable ones [5], ¹ it is natural to expect that the nonperturbative effect is such that $|r_2(D \rightarrow VV)| > |r_2(D \rightarrow VP)| > |r_2(D \rightarrow PP)|$ (V : vector meson, P : pseudoscalar meson) since soft-gluon effects become more important when final-state particles move slower, allowing more time for significant final-state interactions. Numerically, it follows from Eq.(2) that $r_2 \sim -0.67$, $-(0.9 \sim 1.1)$, $-(1.2 \sim 1.3)$ respectively in $D \rightarrow \bar{K}\pi$, $\bar{K}^*\pi$ and $\bar{K}^*\rho$ decays [4], in accordance with the theoretical expectation. It is clear that the leading $1/N_c$ expansion works most successfully for $D \rightarrow \bar{K}\pi$ as the sub-leading $1/N_c$ factorizable contribution is almost compensated by the soft-gluon effect so that $\xi_2(D \rightarrow \bar{K}\pi) \approx 0$.

Now come back to the B meson case. *A priori* there is no reason to expect that a_2 extracted from $B \rightarrow \psi K^{(*)}$ should be the same as that in $B \rightarrow D^{(*)}\pi(\rho)$ decays. Recall

¹Soft gluon contributions are of course nonfactorizable. The fact that $r_{1,2}$ are channel dependent reminds us of that they are originally nonfactorizable.

that the c.m. momentum in $B \rightarrow D\pi$ is 2306 MeV, while it is only 1682 MeV in $B \rightarrow \psi K$ decay. Hence a direct determination of a_2 from $B \rightarrow D^{(*)}\pi(\rho)$ data is desirable and it is expected that $|r_2(D \rightarrow PP)| > |r_2(B \rightarrow \psi K)| \gtrsim |r_2(B \rightarrow D\pi)|$. However, it is easily seen from Tables XX and XXI of Ref.[1] that, based on the modified Bauer-Stech-Wirbel model [6], an individual fit of a_2/a_1 to the CLEO data of $B \rightarrow D^{(*)}\pi(\rho)$ gives rise to

$$\frac{a_2}{a_1} = \begin{cases} 0.31 \pm 0.12, & B \rightarrow D\pi; \\ 0.44 \pm 0.23, & B \rightarrow D\rho; \\ 0.32 \pm 0.13, & B \rightarrow D^*\pi; \\ 0.68 \pm 0.26, & B \rightarrow D^*\rho. \end{cases} \quad (3)$$

Since $r_{1,2}$ are not supposed to vary significantly from $B \rightarrow D\pi$ to $D^*\rho$ decays, a sizeable discrepancy among some of the values of a_2/a_1 shown in (3) determined from various B decay modes is certainly unexpected. Recall that the aforementioned value $a_2/a_1 = 0.23 \pm 0.11$ cited in the CLEO paper [1], which is substantially different from the individual fits given in (3), is obtained by a global least squares fit to the CLEO data. Of course, it is more complicated to extract a_2 from $B \rightarrow D^{(*)}\pi(\rho)$ decays than from $B \rightarrow \psi K^{(*)}$ since the former involve final-state interactions and W -exchange contributions. Nevertheless, even in the absence of the above two effects, a better improvement on the previous theoretical calculations for $B \rightarrow D^{(*)}\pi(\rho)$ is called for.

It is tempted to argue that the above-mentioned difficulty for extracting a_2 is circumvented in the case of $B \rightarrow \psi K^{(*)}$ decays as they are free of final-state strong interactions and nonspectator effects. Indeed, an individual fit of a_2 to the CLEO data of $B^- \rightarrow \psi K^-$, ψK^{*-} , $\bar{B}^0 \rightarrow \psi \bar{K}^0$, $\psi \bar{K}^{*0}$ yields $|a_2| = 0.25 \pm 0.02$, 0.25 ± 0.04 , 0.20 ± 0.03 , 0.24 ± 0.03 , respectively (see Tables IX and XX of Ref.[1]). However, it was pointed out recently that there are two experimental data for $B \rightarrow \psi K^{(*)}$ which cannot be accounted for simultaneously by all commonly used models [7,8]. That is, all the known models in the literature fail to reproduce the data of either the production ratio $R = \Gamma(B \rightarrow \psi K^*)/\Gamma(B \rightarrow \psi K)$ or the fraction of longitudinal polarization Γ_L/Γ in $B \rightarrow \psi K^*$ or both. This casts doubt on the estimate of a_2 from $B \rightarrow \psi K^{(*)}$ and even on the validity of the factorization approach.

In this paper, we will explore the possibility of accounting for the data of $B \rightarrow \psi K^{(*)}$ without giving up the factorization hypothesis. We found that the data of R measured by CLEO and Γ_L/Γ by CDF for $B \rightarrow \psi K^{(*)}$ decays can be accommodated by the heavy flavor symmetry approach for heavy-light form factors with an appropriate choice for their q^2 dependence. This method for heavy-light form factors is then applied to $B \rightarrow D^{(*)}\pi(\rho)$ decays and compared with experiment. We shall see that a_2/a_1 or a_2 extracted in this way is improved quite significantly. A discussion on its implication is then presented.

2. Implications from $B \rightarrow \psi K^{(*)}$ decays The experimental data of interest for $B \rightarrow \psi K^{(*)}$ are the vector to pseudoscalar production ratio [1]

$$R = \frac{\mathcal{B}(B \rightarrow \psi K^*)}{\mathcal{B}(B \rightarrow \psi K)} = 1.71 \pm 0.34, \quad (4)$$

and the fraction of longitudinal polarization in $B \rightarrow \psi K^*$

$$\left(\frac{\Gamma_L}{\Gamma}\right)_{B \rightarrow \psi K^*} = \begin{cases} 0.97 \pm 0.16 \pm 0.15, & \text{ARGUS [9];} \\ 0.80 \pm 0.08 \pm 0.05, & \text{CLEO [1];} \\ 0.66 \pm 0.10^{+0.08}_{-0.10}, & \text{CDF [10].} \end{cases} \quad (5)$$

Based on factorization, it was shown recently that currently used $B \rightarrow K^{(*)}$ form factors fail to explain the data of R and Γ_L/Γ simultaneously [7,8]. This might be attributed either to a failure of the factorization method (see e.g. Ref.[11]) or to a wrong choice of form factors or both.

In what follows we would like to investigate if it is possible to “derive” a set of $B \rightarrow K^{(*)}$ form factors to account for the $B \rightarrow \psi K^{(*)}$ data within the factorization framework. Since the existing models lead to form factors excluded by data [7,8], we prefer to follow Ref.[12] to relate the $B \rightarrow K^{(*)}$ and $D \rightarrow K^{(*)}$ form factors at the same heavy quark velocity v via model-independent heavy flavor symmetry, as elaborated on in Ref.[7]. So long as the momentum of the light meson $p_{K^{(*)}}$ does not scale with $m_{c,b}$ or $v \cdot p_{K^{(*)}} \ll m_{c,b}$, one has the relations [12]²

$$\begin{aligned} F_1^{BK}(q_B^2) &= \frac{C_{bc}}{2\sqrt{m_b m_c}} \left\{ (m_b + m_c) F_1^{DK}(q_D^2) - (m_b - m_c) \frac{m_D^2 - m_K^2}{q_D^2} [F_0^{DK}(q_D^2) - F_1^{DK}(q_D^2)] \right\}, \\ V^{BK^*}(q_B^2) &= C_{bc} \sqrt{\frac{m_c}{m_b}} \frac{m_B + m_{K^*}}{m_D + m_{K^*}} V^{DK^*}(q_D^2), \\ A_1^{BK^*}(q_B^2) &= C_{bc} \sqrt{\frac{m_b}{m_c}} \frac{m_D + m_{K^*}}{m_B + m_{K^*}} A_1^{DK^*}(q_D^2), \\ A_2^{BK^*}(q_B^2) &= \frac{1}{2} C_{bc} \sqrt{\frac{m_c}{m_b}} \left\{ \left(1 + \frac{m_c}{m_b}\right) \frac{m_B + m_{K^*}}{m_D + m_{K^*}} A_2^{DK^*}(q_D^2) + \left(1 - \frac{m_c}{m_b}\right) \frac{m_B + m_{K^*}}{q_D^2} \right. \\ &\quad \times \left. \left[2m_{K^*} A_0^{DK^*}(q_D^2) - (m_D + m_{K^*}) A_1^{DK^*}(q_D^2) + (m_D - m_{K^*}) A_2^{DK^*}(q_D^2) \right] \right\}, \end{aligned} \quad (6)$$

where $C_{bc} = (\alpha_s(m_b)/\alpha_s(m_c))^{-6/25}$, $q_B = m_b v - q$, $q_D = m_c v - q$, and we have followed Ref.[13] for the definition of form factors.

It is customary to make a monopole ansatz for all the form factors F_0 , F_1 , A_0 , A_1 , A_2 , V [13]. However, a careful study based on the scaling argument indicates that not all the form

²Empirically, we found that the heavy-light form-factor relations (6) using the heavy quark masses m_b and m_c work better for $B \rightarrow \psi K^{(*)}$ decays than that using the meson masses m_B and m_D .

factors share the same q^2 behavior. A consideration of the heavy quark limit behavior of the form factors leads to [14]

$$F_0^{BK}(q^2) = F_1^{BK}(q^2) \left(1 - \frac{q^2}{m_B^2 - m_K^2} \right), \quad (7)$$

and

$$A_0^{BK^*}(q^2) = \frac{m_B + m_{K^*}}{2m_{K^*}} A_1^{BK^*}(q^2) - \frac{m_B^2 - m_{K^*}^2 - q^2}{2m_{K^*}(m_B + m_{K^*})} A_2^{BK^*}(q^2) \quad (8)$$

to the leading order in the heavy quark limit. Note that at $q^2 = 0$, (7) and (8) are precisely the constraints [13]

$$\begin{aligned} F_0^{BK}(0) &= F_1^{BK}(0), \\ A_0^{BK^*}(0) &= \frac{m_B + m_{K^*}}{2m_{K^*}} A_1^{BK^*}(0) - \frac{m_B - m_{K^*}}{2m_{K^*}} A_2^{BK^*}(0), \end{aligned} \quad (9)$$

necessary for avoiding unphysical poles on the r.h.s. of Eq.(6). It is evident that the q^2 dependence of F_1 is different from that of F_0 by an additional pole factor. Several theoretical arguments and many QCD sum rule calculations [15-18] indicate that $F_1(q^2)$ has a monopole behavior. This in turn implies an approximately constant F_0 .³

If A_0 and A_1 have the same q^2 dependence, Eq.(8) will lead to an interesting q^2 behavior for A_2 [14]. Assuming

$$A_0(q^2) = \frac{A_0(0)}{\left(1 - \frac{q^2}{m^2}\right)^n}, \quad A_1(q^2) = \frac{A_1(0)}{\left(1 - \frac{q^2}{m^2}\right)^n}, \quad (10)$$

where the pole mass m is the same for A_0 and A_1 in the heavy quark limit, we see from Eq.(8) that, by neglecting m_{K^*} relative to m_B , the q^2 dependence of A_2 is different from that of A_0 and A_1 by an additional pole factor [14]:

$$A_2(q^2) = \frac{A_2(0)}{\left(1 - \frac{q^2}{m^2}\right)^{n+1}}. \quad (11)$$

In practice, we will take $n = 0, 1$.

In the following we will calculate $B \rightarrow K^{(*)}$ form factors from Eq.(6) using the experimental input on $D \rightarrow K^{(*)}$ ones [20]:⁴

$$\begin{aligned} F_1^{DK}(0) &= 0.77 \pm 0.04, & V^{DK^*}(0) &= 1.12 \pm 0.16, \\ A_1^{DK^*}(0) &= 0.61 \pm 0.05, & A_2^{DK^*}(0) &= 0.45 \pm 0.09. \end{aligned} \quad (12)$$

³It was pointed out in Ref.[19] that if the single pole behavior holds for both F_0 and F_1 , one is led to $f_-^{B\pi}(0) = -0.21 f_+^{B\pi}(0)$, which is inconsistent with the heavy-quark-symmetry relation $f_-^{B\pi} \approx -f_+^{B\pi}$. A nearly constant behavior of F_0 in q^2 is confirmed by a recent QCD-sum-rule calculation [17].

⁴The average experimental values given in the Particle Data Group [21] are $F_1^{DK}(0) = 0.75 \pm 0.03$, $V^{DK^*}(0) = 1.1 \pm 0.2$, $A_1^{DK^*}(0) = 0.56 \pm 0.04$, $A_2^{DK^*}(0) = 0.40 \pm 0.08$.

As for the q^2 dependence, since A_2 has one more pole factor than A_0 and A_1 , as just discussed, two possibilities of interest are:

(i) a monopole form for F_1 , A_2 , V , and an approximately constant for F_0 , A_0 , A_1 . Recall that a slowly varying $A_1(q^2)$ with q^2 is strongly advocated in Ref.[8].

(ii) a monopole extrapolation for F_1 , A_0 , A_1 , a dipole behavior for A_2 , V , and an approximately constant for F_0 . This is precisely the pole behavior shown by a recent QCD sum rule analysis [18].⁵

In addition to the above two cases, we also consider case (iii) in which all the form factors are extrapolated in a monopole form, as employed in the Bauer-Stech-Wirbel (BSW) model [13]. Given a set of extrapolation procedures, the $D \rightarrow K^{(*)}$ form factors are first extrapolated from $q^2 = 0$ to maximum q_D^2 , and then related to the $B \rightarrow K^{(*)}$ form factors at zero recoil via Eq.(6). Using $m_b = 5$ GeV and $m_c = 1.5$ GeV, the calculated $B \rightarrow K^{(*)}$ form factors at $q^2 = 0$ and m_ψ^2 are summarized in Table I. For a comparison, we have included in Table I two other model predictions: (1) the BSW model (BSWI) [13] in which the $B \rightarrow K^{(*)}$ form factors are first calculated at $q^2 = 0$ and then extrapolated to finite q^2 using a monopole behavior for all the form factors, and (2) the modified BSW model (BSWII) [5], which is the same as BSWI except for a dipole q^2 dependence for form factors F_1 , A_0 , A_2 , V , inspired by the q^2 behavior for heavy-heavy meson transitions [5].

Table I. $B \rightarrow K^{(*)}$ form factors evaluated at $q^2 = 0$ and m_ψ^2 in various form-factor models.

	(i)	(ii)	(iii)	BSWI	BSWII
$F_1^{BK}(0), F_1^{BK}(m_\psi^2)$	0.56 0.84	0.56 0.84	0.47 0.70	0.38 0.56	0.38 0.83
$V^{BK^*}(0), V^{BK^*}(m_\psi^2)$	0.70 1.04	0.33 0.72	0.70 1.04	0.37 0.55	0.37 0.81
$A_1^{BK^*}(0), A_1^{BK^*}(m_\psi^2)$	0.55 0.55	0.29 0.41	0.29 0.41	0.33 0.46	0.33 0.46
$A_2^{BK^*}(0), A_2^{BK^*}(m_\psi^2)$	0.26 0.36	0.19 0.36	0.31 0.43	0.33 0.46	0.33 0.64

With the $B \rightarrow K^{(*)}$ form factors given in Table I, it is straightforward to compute the quantities R and Γ_L/Γ (see [7,8] for their kinematic expressions). The results are tabulated in Table II. We see that the heavy-flavor-symmetry approach for heavy-light form factors with type (ii) of q^2 dependence gives a satisfactory agreement with the CLEO measurement of R and CDF data of Γ_L/Γ . However, if the recent observation of a large fraction ($\geq 70\%$) of the longitudinal polarization in $B \rightarrow \psi K^*$ by ARGUS [9] and CLEO [1] is confirmed in the future, then case (ii) will be ruled out either. Note that the factorization hypothesis

⁵The unusual q^2 behaviors for the form factors A_1 and A_2 obtained in existing QCD-sum-rule calculations [16] are no longer seen in a recent similar work [18].

leads to a theoretical upper bound 0.83 for Γ_L/Γ (see e.g. Ref.[7]). This means that if the measured Γ_L/Γ is larger than 0.83, one can conclude that the factorization approach fails irrespective of the choice of form factors. Hence, a refined measurement of the fraction of longitudinal polarization in $B \rightarrow \psi K^*$ is urgently called for.

Table II. Predictions for R and Γ_L/Γ in various form-factor models.

	(i)	(ii)	(iii)	BSWI	BSWII	Experiment
R	4.00	1.84	2.83	4.23	1.61	1.71 ± 0.34 [1]
$\frac{\Gamma_L}{\Gamma}$	0.61	0.56	0.41	0.57	0.35	$\left\{ \begin{array}{ll} 0.97 \pm 0.22 & \text{ARGUS [9]} \\ 0.80 \pm 0.09 & \text{CLEO [1]} \\ 0.66^{+0.13}_{-0.14} & \text{CDF [10]} \end{array} \right.$

Before proceeding further, we would like to give a brief summary on how many parameters are being fitted in this procedure. To describe $B \rightarrow \psi K(K^*)$ decays we need six form factors: $F_{0,1}^{BK}$, $A_{0,1,2}^{BK^*}$ and V^{BK^*} at $q^2 = m_\psi^2$. They are related to $D \rightarrow K^{(*)}$ form factors at the same heavy quark velocity but near zero recoil by model-independent heavy flavor symmetry. Using the experimental input on $D \rightarrow K^{(*)}$ form factors at $q^2 = 0$, we are able to determine $B \rightarrow K^{(*)}$ form factors at any finite q^2 provided that their q^2 dependence is known. Since F_1 (A_2) has one more pole factor than F_0 (A_0 and A_1) and many model calculations indicate that F_1 is of monopole form, it follows that only two of the form factors, say A_2 and V , are needed to fit data to determine their q^2 behavior. In short, the q^2 extrapolation of F_1 is fixed by models, while A_2 and V by data.

We next turn to the determination of the parameter a_2 . Using $V_{cb} = 0.040$ [22], $\tau(B^-) = 1.54 \times 10^{-12}s$ [21], $f_\psi = 395$ MeV extracted from the measured width of $\psi \rightarrow e^+e^-$ [21], and assuming factorization, we find

$$\begin{aligned}
\mathcal{B}(B^- \rightarrow \psi K^-) &= 2.85 \times 10^{-2} \left| a_2 F_1^{BK}(m_\psi^2) \right|^2 = 1.99 \times 10^{-2} |a_2|^2, \\
\mathcal{B}(B^- \rightarrow \psi K^{*-}) &= 0.221 \left| a_2 A_1^{BK^*}(m_\psi^2) \right|^2 = 3.67 \times 10^{-2} |a_2|^2,
\end{aligned} \tag{13}$$

where we have applied type-(ii) form factors given in Table I. From the CLEO data [1]

$$\begin{aligned}
\mathcal{B}(B^- \rightarrow \psi K^-) &= (0.110 \pm 0.017)\%, \quad \mathcal{B}(B^0 \rightarrow \psi K^0) = (0.075 \pm 0.025)\%, \\
\mathcal{B}(B^- \rightarrow \psi K^{*-}) &= (0.178 \pm 0.056)\%, \quad \mathcal{B}(B^0 \rightarrow \psi K^{*0}) = (0.169 \pm 0.036)\%,
\end{aligned} \tag{14}$$

the respective $|a_2|$ is found to be 0.235 ± 0.018 , 0.192 ± 0.032 , 0.220 ± 0.035 , 0.212 ± 0.023 , where use of $\tau(B^0) = 1.50 \times 10^{-12}s$ [21] has been made. Therefore, the combined value is

$$\left| a_2(B \rightarrow \psi K^{(*)}) \right| = 0.221 \pm 0.012. \tag{15}$$

3. Moral from $B \rightarrow K^*\gamma$ decays We see in the previous section that the approach of heavy flavor symmetry for heavy-light form factors with type (ii) of q^2 dependence is favored by the $B \rightarrow \psi K^{(*)}$ data. We shall see in this section that this method for heavy-light form factors also gives an excellent description of $B \rightarrow K^*\gamma$ decay, from which useful information on the form factors $V(0)$ and $A_1(0)$ can be extracted.

In the standard model, the weak radiative decay $B \rightarrow K^*\gamma$ is dominated by the short-distance penguin transition $b \rightarrow s\gamma$. The transition amplitude for $b \rightarrow s\gamma$ reads [23]

$$A(b \rightarrow s\gamma) = i \frac{G_F}{\sqrt{2}} \frac{e}{8\pi^2} F_2(x_t) V_{tb} V_{ts}^* \varepsilon^\mu k^\nu \bar{s} \sigma_{\mu\nu} [m_b(1 + \gamma_5) + m_s(1 - \gamma_5)] b, \quad (16)$$

where F_2 is a smooth function of $x_t \equiv m_t^2/M_W^2$ [23]; $F_2 \cong 0.65$ for $m_t = 174$ GeV and $\Lambda_{\text{QCD}} = 200$ MeV. In the static limit of the heavy b quark, we may use the equation of motion $\gamma_0 b = b$ to derive the relation [12]

$$\langle K^* | \bar{s} i \sigma_{0i} (1 \pm \gamma_5) b | B \rangle = \langle K^* | \bar{s} \gamma_i (1 \mp \gamma_5) b | B \rangle. \quad (17)$$

As a result, the form factors f_1 and f_2 in the matrix elements of the tensor current can be related to the form factors A_1 and V at the same q^2 . At $q^2 = 0$ we have (see e.g. Ref.[24])

$$f_1^{BK^*}(0) = -2f_2^{BK^*}(0) = - \left(\frac{m_B - m_{K^*}}{m_B} V^{BK^*}(0) + \frac{m_B + m_{K^*}}{m_B} A_1^{BK^*}(0) \right). \quad (18)$$

The decay rate is then given by

$$\Gamma(B \rightarrow K^*\gamma) = \frac{1}{32\pi} \left(\frac{m_B^2 - m_{K^*}^2}{m_B} \right)^3 \left| \frac{G_F}{\sqrt{2}} \frac{e}{8\pi^2} F_2 V_{tb} V_{ts}^* m_b \right|^2 \left(|f_1^{BK^*}(0)|^2 + 4 |f_2^{BK^*}(0)|^2 \right). \quad (19)$$

Hence, to the leading order in $1/m_b$ expansion

$$\mathcal{B}(B \rightarrow K^*\gamma) = 1.32 \times 10^{-4} \left| A_1^{BK^*}(0) \right|^2 \left(1 + 0.711 V^{BK^*}(0)/A_1^{BK^*}(0) \right)^2 + \mathcal{O}(1/m_b^2), \quad (20)$$

where use has been made of the relation $V_{tb} V_{ts}^* \cong -V_{cb} V_{cs}^*$.

The prediction for the branching ratio of $B \rightarrow K^*\gamma$ in the heavy-flavor-symmetry approach for form factors with various types of q^2 extrapolation is exhibited in Table III. The agreement between case (ii) and the CLEO experiment [25] is excellent. The measured branching ratio for $B \rightarrow K^*\gamma$ together with its theoretical prediction (20) thus provides useful constraints on the form factors $V^{BK^*}(0)$ and $A_1^{BK^*}(0)$.

Table III. Predictions for the branching ratio of $B \rightarrow K^*\gamma$ in various form-factor models.

	(i)	(ii)	(iii)	Experiment [25]
$\mathcal{B}(B \rightarrow K^*\gamma)$	1.5×10^{-4}	3.6×10^{-5}	8.5×10^{-5}	$(4.5 \pm 1.5 \pm 0.9) \times 10^{-5}$

4. Analyses of $B \rightarrow D(D^*)\pi(\rho)$ decays We learn from previous two sections that $B \rightarrow \psi K^{(*)}$ and $B \rightarrow K^*\gamma$ decays are satisfactorily described by the heavy-flavor-symmetry approach for heavy-light form factors provided that F_0 behaves as a constant, F_1 , A_0 , A_1 have a monopole behavior, and the q^2 dependence of A_2 and V is of the dipole form. In this section we will apply this method to $B \rightarrow D^{(*)}\pi(\rho)$ decays to extract a_1 and a_2 . For recent analyses of $B \rightarrow D^{(*)}\pi(\rho)$ decays, see Ref.[26].

As stressed in passing, there exist two complications for evaluating the $\bar{B}^0 \rightarrow D^{(*)+}\pi^-(\rho^-)$ decay amplitudes. First, the W -exchange diagram contributes to \bar{B}^0 decay, but it is difficult to estimate its size. Second, there are final-state interactions (FSI) since the decay amplitudes involve isospin 1/2 and 3/2 channels. In what follows we will first analyze the data without considering these two effects, and then come back to them later on. Based on factorization, we obtain

$$\begin{aligned}\mathcal{B}(\bar{B}^0 \rightarrow D^+\pi^-) &= 0.80 \times 10^{-2} \left| a_1 F_0^{BD}(m_\pi^2) \right|^2, \\ \mathcal{B}(\bar{B}^0 \rightarrow D^+\rho^-) &= 1.93 \times 10^{-2} \left| a_1 F_1^{BD}(m_\rho^2) \right|^2, \\ \mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\pi^-) &= 0.75 \times 10^{-2} \left| a_1 A_0^{BD^*}(m_\pi^2) \right|^2, \\ \mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\rho^-) &= 0.11 \times 10^{-2} \left| a_1 A_1^{BD^*}(m_\rho^2) \right|^2 H,\end{aligned}\tag{21}$$

and

$$\begin{aligned}R_1 \equiv \frac{\mathcal{B}(B^- \rightarrow D^0\pi^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^+\pi^-)} &= \frac{\tau(B^-)}{\tau(\bar{B}^0)} \left(1 + \frac{m_B^2 - m_\pi^2}{m_B^2 - m_D^2} \frac{f_D}{f_\pi} \frac{F_0^{B\pi}(m_D^2)}{F_0^{BD}(m_\pi^2)} \frac{a_2}{a_1} \right)^2, \\ R_2 \equiv \frac{\mathcal{B}(B^- \rightarrow D^0\rho^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^+\rho^-)} &= \frac{\tau(B^-)}{\tau(\bar{B}^0)} \left(1 + \frac{f_D}{f_\rho} \frac{A_0^{B\rho}(m_D^2)}{F_1^{BD}(m_\rho^2)} \frac{a_2}{a_1} \right)^2, \\ R_3 \equiv \frac{\mathcal{B}(B^- \rightarrow D^{*0}\pi^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\pi^-)} &= \frac{\tau(B^-)}{\tau(\bar{B}^0)} \left(1 + \frac{f_{D^*}}{f_\pi} \frac{F_1^{B\pi}(m_{D^*}^2)}{A_0^{BD^*}(m_\pi^2)} \frac{a_2}{a_1} \right)^2, \\ R_4 \equiv \frac{\mathcal{B}(B^- \rightarrow D^{*0}\rho^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\rho^-)} &= \frac{\tau(B^-)}{\tau(\bar{B}^0)} \left(1 + 2\eta \frac{H_1}{H} + \eta^2 \frac{H_2}{H} \right),\end{aligned}\tag{22}$$

with

$$\begin{aligned}\eta &= \frac{m_{D^*}(m_B + m_\rho)}{m_\rho(m_B + m_{D^*})} \frac{f_{D^*}}{f_\rho} \frac{A_1^{B\rho}(m_{D^*}^2)}{A_1^{BD^*}(m_\rho^2)} \frac{a_2}{a_1}, \\ H &= (a - bx)^2 + 2(1 + c^2 y^2), \\ H_1 &= (a - bx)(a - b'x') + 2(1 + cc'yy'), \\ H_2 &= (a - b'x')^2 + 2(1 + c'^2 y'^2),\end{aligned}\tag{23}$$

and

$$a = \frac{m_B^2 - m_{D^*}^2 - m_\rho^2}{2m_{D^*}m_\rho}, \quad b = \frac{2m_B^2 p_c^2}{m_{D^*}m_\rho(m_B + m_{D^*})^2}, \quad c = \frac{2m_B p_c}{(m_B + m_{D^*})^2},$$

$$x = \frac{A_2^{BD*}(m_\rho^2)}{A_1^{BD*}(m_\rho^2)}, \quad y = \frac{V^{BD*}(m_\rho^2)}{A_1^{BD*}(m_\rho^2)}, \quad (24)$$

where p_c is the c.m. momentum, and b', c', x', y' are obtained from b, c, x, y respectively with the replacement $D^* \leftrightarrow \rho$; for instance, $x' = A_2^{B\rho}(m_{D^*}^2)/A_1^{B\rho}(m_{D^*}^2)$.

The heavy-heavy form factors e.g. F_0^{BD} , A_1^{BD*} appearing in (21-22) can be related to a universal Isgur-Wise function $\xi(v \cdot v')$ via heavy quark symmetry [5]. We will use the $B \rightarrow D^{(*)}$ form factors evaluated in Ref.[5], which include $1/m_Q$ corrections. As for the heavy-light form factor $F_1^{B\pi}$, we get $F_{0,1}^{B\pi}(0) = 0.48$ using $F_{0,1}^{D\pi}(0) \approx 0.83$ derived from $D^+ \rightarrow \pi^+\pi^0$ decay [27].⁶ In the absence of experimental input for $D \rightarrow \rho$ form factors, we will assume SU(3) flavor symmetry for $D \rightarrow \rho$ and $B \rightarrow \rho$ form factors at $q^2 = 0$, namely $A_{1,2}^{B(D)\rho}(0) \approx A_{1,2}^{B(D)K^*}(0)$, $V^{B(D)\rho}(0) \approx V^{B(D)K^*}(0)$.⁷ As for the decay constants, we use $f_\pi = 132$ MeV, $f_\rho = 216$ MeV, $f_D = 208$ MeV [28], and $f_{D^*}/f_D \approx 1.28$ [29]. Numerical results are summarized in Table IV, where we have used $\tau(B^-)/\tau(B^0) = 1.027$ from PDG [21]. A fit to the measured branching ratios of $\bar{B}^0 \rightarrow D^{(*)}\pi(\rho)$ determines the parameter a_1 , while the ratio a_2/a_1 listed in Table IV is extracted either from the measured ratios R_1, \dots, R_4 or from $B^- \rightarrow D^{(*)}\pi(\rho)$ decays together with the a_1 obtained in the corresponding \bar{B}^0 decays.

The combined value of a_1 obtained from Table IV is

$$a_1(B \rightarrow D^{(*)}\pi(\rho)) = 1.012 \pm 0.057. \quad (25)$$

We see that our values of a_2/a_1 are improved substantially over the previous results obtained using the BSWII model [see Eq.(3)]. We also note that the magnitude of a_2/a_1 determined in this manner is in general quite stable except for $B^- \rightarrow D^{*0}\rho^-$ or R_4 . Therefore, a refined measurement of this decay mode is greatly welcome. Excluding the data from $B^- \rightarrow D^{*0}\rho^-$, the combined value of a_2/a_1 extracted from the remaining B^- decay modes is found to be

$$\frac{a_2}{a_1}(B \rightarrow D^{(*)}\pi(\rho)) = 0.224 \pm 0.058. \quad (26)$$

Note that the corresponding combined value of a_2/a_1 obtained in the BSWII model [see Eq.(3)] is 0.33 ± 0.08 . Combining (26) with (25) leads to

$$a_2(B \rightarrow D^{(*)}\pi(\rho)) = 0.226 \pm 0.060. \quad (27)$$

⁶The prediction $F_{0,1}^{B\pi}(0) = 0.48$ is close to the value of 0.53 obtained in the framework of chiral perturbation theory that incorporates chiral and heavy quark symmetries [19]. Note that $F_1^{D\pi}(0) > F_1^{DK}(0)$, whereas $F_1^{B\pi}(0) < F_1^{BK}(0)$.

⁷We have checked explicitly that, assuming $A_{1,2}^{D\rho}(0) = A_{1,2}^{DK^*}(0)$ and $V^{D\rho}(0) = V^{DK^*}(0)$, SU(3) flavor symmetry for $B \rightarrow \rho$ and $B \rightarrow K^*$ form factors at finite q^2 obtained using Eq.(6) with type-(ii) q^2 dependence is better than 10%.

The main theoretical uncertainty comes from the form factors $A_{1,2}^{B\rho}$ and $V^{B\rho}$, for which we lack experimental input on $D \rightarrow \rho$ form factors. At this point, we wish to emphasize again that, in contrast to Ref.[1], our value for a_2/a_1 is not obtained by a least squares fit to the data. Recall that a global fit of the BSWII model to the data yields $a_2/a_1 = 0.23 \pm 0.11$ [1]. Our result (27) thus improves the previous error analysis by a factor of two. We also remark that the fraction of longitudinal polarization in $\bar{B}^0 \rightarrow D^{*+}\rho^-$ is measured to be $0.93 \pm 0.05 \pm 0.05$ [1]. Unlike the $B \rightarrow \psi K^*$ case, this relative amount of longitudinal polarization is easily accounted for by theory, which is predicted to be 88%.

Table IV. Extraction of a_1 and a_2/a_1 from various $B \rightarrow D(D^*)\pi(\rho)$ decays by comparing the theoretical prediction for branching ratios with experiment.

	$\mathcal{B}(\%)_{\text{theory}}$	$\mathcal{B}(\%)_{\text{expt [1]}}$	a_1	a_2/a_1
$\bar{B}^0 \rightarrow D^+\pi^-$	$0.270a_1^2$	0.29 ± 0.07	1.04 ± 0.13	-
$\bar{B}^0 \rightarrow D^+\rho^-$	$0.673a_1^2$	0.81 ± 0.21	1.10 ± 0.14	-
$\bar{B}^0 \rightarrow D^{*+}\pi^-$	$0.260a_1^2$	0.26 ± 0.05	1.00 ± 0.10	-
$\bar{B}^0 \rightarrow D^{*+}\rho^-$	$0.806a_1^2$	0.74 ± 0.17	0.96 ± 0.11	-
$B^- \rightarrow D^0\pi^-$	$0.277a_1^2(1 + 1.497a_2/a_1)^2$	0.55 ± 0.07	1.04 ± 0.13	0.24 ± 0.10
$B^- \rightarrow D^0\rho^-$	$0.690a_1^2(1 + 1.131a_2/a_1)^2$	1.35 ± 0.19	1.10 ± 0.14	0.24 ± 0.14
$B^- \rightarrow D^{*0}\pi^-$	$0.267a_1^2(1 + 1.918a_2/a_1)^2$	0.52 ± 0.10	1.00 ± 0.10	0.21 ± 0.08
$B^- \rightarrow D^{*0}\rho^-$	$0.827a_1^2(1 + 1.446a_2/a_1)^2$	1.68 ± 0.35	0.96 ± 0.11	0.34 ± 0.13

Thus far we have neglected FSI and nonspectator effects. Experimentally, FSI can be tested by measuring the decay rates of $B^- \rightarrow D^{(*)0}\pi^-(\rho^-)$, $\bar{B}^0 \rightarrow D^{(*)+}\pi^-(\rho^-)$, $D^{(*)0}\pi^0(\rho^0)$ to deduce the isospin amplitudes $A_{1/2}$, $A_{3/2}$ and the phase-shift difference $(\delta_{1/2} - \delta_{3/2})$. Moreover, in the absence of W exchange, a_2/a_1 can be determined from $A_{3/2}/A_{1/2}$; for example, in $B \rightarrow D\pi$ decay [30]

$$\frac{m_B^2 - m_\pi^2}{m_B^2 - m_D^2} \frac{f_D}{f_\pi} \frac{F_0^{B\pi}(m_D^2)}{F_0^{BD}(m_\pi^2)} \frac{a_2}{a_1} = 1.497 \frac{a_2}{a_1} = 2 \frac{A_{3/2}/A_{1/2} - \frac{1}{\sqrt{2}}}{A_{3/2}/A_{1/2} + \sqrt{2}}. \quad (28)$$

Unfortunately, an observation of $\bar{B}^0 \rightarrow D^0\pi^0$ is still not available yet.

The presence of W exchange will affect the determination of a_1 from \bar{B}^0 decays. Theoretically, the W -exchange amplitude receives its main contribution from nonperturbative color octet currents [4], which is difficult to estimate. Though both nonspectator and FSI effects are known to be important in charm decays, it is generally believed that they do not play a significant role in bottom decay as the decay particles are moving fast, not allowing adequate time for FSI.

5. Discussion and conclusion We see from (15) and (27) that the magnitude of a_2 determined from $B \rightarrow D^{(*)}\pi(\rho)$ decays agrees well with that extracted from $B \rightarrow \psi K^{(*)}$. Then, can we conclude that a_2 extracted in the latter decay is positive? Recall that, as we have argued before, nonperturbative effects must be in such a way that $|r_2(B \rightarrow \psi K^{(*)})| \gtrsim |r_2(B \rightarrow D^{(*)}\pi)|$ [4]. Since $a_2(B \rightarrow D^{(*)}\pi) = (c_2 + c_1/N_c) + \frac{1}{2}r_2c_1$ is positive and $c_2 + c_1/N_c = 0.15 \sim 0.20$ at $\mu = m_b$ beyond the leading logarithmic approximation [31],⁸ it is clear that $r_2(B \rightarrow D^{(*)}\pi) = 0.05 \sim 0.14$ is positive. Now there are two possibilities for a_2 in $B \rightarrow \psi K^{(*)}$: (i) $r_2 > 0$; this implies a positive a_2 and that $a_2(B \rightarrow \psi K^{(*)}) \gtrsim a_2(B \rightarrow D^{(*)}\pi)$, and (ii) $r_2 < 0$; this together with (15) indicates a negative a_2 and $r_2(B \rightarrow \psi K^{(*)}) = -(0.72 \sim 0.80)$. We consider the case (ii) very unlikely since the magnitude of r_2 in $B \rightarrow \psi K^{(*)}$ should not deviate too much from that in $B \rightarrow D^{(*)}\pi$. Therefore, contrary to the previous publication [4], we believe that $a_2(B \rightarrow \psi K^{(*)})$ ought to be positive. In fact, it is not difficult to achieve the relation $a_2(B \rightarrow \psi K^{(*)}) \gtrsim a_2(B \rightarrow D^{(*)}\pi)$. Note that our extraction of $a_{1,2}$ from $B \rightarrow D^{(*)}\pi(\rho)$ so far is based on the assumption that FSI and W exchange are negligible. It is likely that the inclusion of these two effects will reduce the present estimate of $a_2(B \rightarrow D^{(*)}\pi(\rho))$. In view of this, a measurement of $\bar{B}^0 \rightarrow D^{(*)0}\pi^0(\rho^0)$ is urgently needed. Finally, the question of why r_2 is positive in exclusive B decays whereas it is negative in D decays remains an enigma. This will be a great challenge to both lattice and QCD-sum-rule practitioners. Nevertheless, the small magnitude of r_2 in $B \rightarrow D^{(*)}\pi(\rho)$ compared to that in exclusive two-body D decays ($|r_2| = (0.67 \sim 1.3)$) is consistent with our expectation that nonfactorizable soft-gluon effects are much less significant in the former. This also explains why the $1/N_c$ approach, which is empirically known to be operative in charm decays, fails in $B \rightarrow D^{(*)}\pi(\rho)$ and $B \rightarrow \psi K^{(*)}$ decays.

To conclude, we have shown that, based on factorization, the heavy-flavor-symmetry approach for heavy-light form factors in conjunction with the type-(ii) q^2 dependence provides a satisfactory description of the CLEO data on $\mathcal{B}(B \rightarrow \psi K^*)/\mathcal{B}(B \rightarrow \psi K)$ and the CDF data on the fraction of the longitudinal polarization in $B \rightarrow \psi K^*$ decays. However, if the measured Γ_L/Γ is larger than 0.70, then our form factors are also ruled out. Furthermore, we will conclude that the factorization approach fails irrespective the choice of form factors if the relative amount of the transverse polarization is found to be less than 17%. Therefore, a refined measurement of Γ_L/Γ in $B \rightarrow \psi K^*$ is urgently needed in order to test form-factor models and the factorization hypothesis. Armed with the above method, we have extracted the parameters a_1 and a_2 from $B \rightarrow \psi K^{(*)}$ and $B \rightarrow D^{(*)}\pi(\rho)$ decays. Our result $a_2/a_1 = 0.22 \pm 0.06$ improves the previous error analysis by a factor of two. Finally, we have argued that the sign of $a_2(B \rightarrow \psi K^{(*)})$ should be positive and we have discussed its

⁸To the leading logarithmic approximation, $c_1(m_b) \sim 1.11$, $c_2(m_b) \sim -0.26$ and hence $c_2 + c_1/N_c \sim 0.11$.

important implications.

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